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Comprehensive Comparison of High Voltage Polymer and Porcelain Insulators in AC Systems

Chavan Vrushank Santoshbhai[1], Anil S. Khopkar[2], Hiren M. Patel[3]

[1]ME Student, Electrical Engg. Department, FoTE, The Maharaja Sayajirao University, Vadodara, India

[2]Asst. Director & Head of Division R&D, Electrical Research and Development Association (ERDA), Vadodara, India

[3]Assistant Professor, Electrical Engg. Department, FoTE, The Maharaja Sayajirao University, Vadodara, India

ABSTRACT: In electrical power system insulator are connected to provide isolation between live parts to ground and also to provide the mechanical support to conductors. Insulators are made with ceramic, toughen glass or composite materials. Now a days composite insulators are more popularly connected in the system. For the system reliability the quality of the insulators needs to be verified before insulators are connected in to the system. The failures of the insulators must be reduced to improve the system reliability. Generally the utility decides the type of insulators based on the environmental conditions, performance of insulators under polluted atmosphere, level of pollution, requirements of dielectric strength as insulation coordination and mechanical strength etc. In this paper the comprehensive comparison of ceramic and polymer insulators used in HVAC system have been presented. Comparison of various electrical and mechanical performance parameters, life span, etc for ceramic and composite insulators have been described in details.

KEYWORDS: High Voltage Insulators, Polymer Insulators, Porcelain Insulators, Insulator Performance, Insulator Characteristics, Comparison

I. INTRODUCTION

High-voltage insulators constitute essential components of power transmission systems, fulfilling dual roles in providing electrical insulation between live conductors and ground, as well as mechanical support for transmission lines [1]. The operation of these insulators directly affects the reliability as well as operational safety of the gird, hence it becomes mandatory to understand the functional characteristics under various environmental and electrical stresses [2]. This review meticulously compares both high voltage polymer and porcelain insulators and discusses their advantages and disadvantages under various conditions that are encountered in AC system [3]. This comprehensive analysis will delve into the electrical, mechanical and environmental performance aspect of both the insulators providing insights which is crucial for optimal selection and design of insulators for AC system [4]. Historically, porcelain insulator had been extensively used due to their inherent robust dielectric properties, stable permittivity and leakage resistance across wide range of temperature and humidity level. It is less prone to sudden changes in electric field distribution under environmental stressor. Porcelain is inherently resistant to UV radiations, temperature fluctuations. Unlike organic materials it do not degrade under sunlight or environmental stresses, maintaining consistent performance over a period of time [5]. Porcelain insulator has excellent compressive and tensile strength which makes them capable to withstand significant mechanical loads such as conductor weight, wind, and ice loading [6]. However, the introduction of polymer insulators marked a paradigm shift, driven by their hydrophobicity and lightweight design, leading to widespread adoption in modern system. This widespread adoption is largely attributed to their enhanced electrical insulating characteristics, ease of manufacturing complex geometries and reduced dimensions along with exceptional mechanical strength. Consequently, the proportion of polymeric materials adopted in high voltage application is constantly increasing due to these advantages [7]. Despite these advantages polymer insulators faces challenges related to degradation and ageing under various environmental and pollution conditions which is not a major concern for traditional ceramic insulators [8].

The evolution of high voltage insulators had seen a transition from very high weight, rigid insulating material like porcelain, glass to lighter and more flexible polymer insulator, this represents the need to reduce cost improve reliability under demanding environmental conditions [9]. Initially ceramic and glass insulators were intensively used but their limitations such as substantial weight and susceptibility to environmental pollution had spurred for the development for polymer insulator [10]. This advancement led to introduction of polymer insulator in 1970s which provided exceptional hydrophobicity as compared to its predecessor ceramic insulators, which had significantly brought down the flashover related incidents, further the ability to mould the polymer material had led manufacturing of complex and optimized design which had significantly improved the performance of the polymeric insulator [10]. This ease of fabrication allows for additional features which enhance the overall performance of polymer insulator [11]. Recent development of high voltage polymer insulator focuses on improving environmental degradation resistance and optimizing design for specific environmental challenges, improving system reliability and long term performance [12].

II. PORCELAIN INSULATOR

Porcelain insulators for long had been a cornerstone in transmission system due to their robust mechanical strength and excellent dielectric properties, Decades of operational deployment of ceramic insulators proved their reliability and resilience under challenging conditions [13].

A. Material Composition and Manufacturing

Porcelain insulators are manufactured from ceramic materials composed primarily of kaolinite clay, feldspar, quartz, and industrial alumina to augment mechanical strength, through elaborate physicochemical and thermal treatments [14]. High temperature sintering is also carried out during the manufacturing process which results in compact and vitrified structure producing superior electrical insulation properties which is indispensable for high voltage application. The vitrification process substantially reduces porosity thus preventing moisture penetration and ensure good dielectric strength over long period of time [15]. Such intrinsic impermeability prevents degradation led by contaminants and atmospheric pollutants [16]. Additionally sleek glazed surface of the insulator prevents adhesion of pollutants which are generally responsible for pollution related flashover especially in contaminated environment [17].

B. Electrical Characteristics

Porcelain insulators exhibit very high dielectric strength, low dielectric loss and high insulation resistance, thus preventing leakage current and flashover under various operating conditions. Their stable electrical performance is attributed to inherent chemical stability and crystalline structure of ceramic material which resist degradation from electrical stresses and environmental factors [18]. This intrinsic stability ensures consistent performance under prolonged electric fields and thermal cycling without occurrence of insulation breakdown [19].Moreover porcelain's high resistance and robust dielectric property withstand severe over voltage conditions maintaining the reliability under transient electrical events [20].The specific composition of raw material , such as percentage content of alumina and silica can significantly influence these electrical characteristics, with this formulation dielectric constants up to 9.80 and flashover voltages exceeding 5KV at 50 Hz had been achieved [21].These desired electrical characteristics can be achieved with carful control over the manufacturing process and material ratios, with specific firing temperature and durations resulted into the formation of dense , non-porous microstructure [22].

C. Mechanical Properties

under service condition high voltage insulators undergoes variety of mechanical stresses such as conductor tension, vibrational forces, wind loads etc. all such challenges demands exceptional tensile, comprehensive and flexure strengths for reliable operation. Key mechanical strength of porcelain insulators include resistance to compression, bending and tension, making them capable of enduring significant static and dynamic loads encountered in transmission lines [23].This robust mechanical integrity is very important factor for supporting weight of conductors and resisting forces from storm, wind etc., ensuring stability of entire grid infrastructure [24].These mechanical properties are very crucial for their structural integrity and long term performance in challenging environments [25].The physical and mechanical integrity of porcelain insulators are significantly affected by the proportion of materials added such as alumina and silica, which can enhance overall strength and resistance to degradation [26].

D. Environmental Performance

Porcelain insulators had demonstrated consistent performance under diverse environmental conditions such as UV radiations, high temperature and pollution conditions due to their inherent inertness and stable molecular structure [27]. This inherent stability contribute to good environmental aging performance as well as mechanical performance, moreover porcelain insulators show excellent resistance to material degradation caused by electrical stress and discharge activities [28].Porcelain insulators demonstrate exceptional thermal stability, resisting degradation across a wide range of temperatures which is desirable for its reliable operation under diverse climatic conditions [29].Their chemical inertness contribute to their longevity in polluted environmental conditions, The smooth glazed surface of porcelain insulators prevent the accumulation of contaminants , thereby reducing flashover incidents in polluted areas [30].

E. Limitations

Despite all the advantage porcelain insulators are characterized by their considerable weight and bulkiness and this complicate transportation and installation procedure. Porcelain insulators have disadvantages such as regular washing and cleaning which is required especially in polluted areas like coastal and industrial location. As these insulators are susceptible to brittle fracture, they require careful handling during installation and maintenance activities moreover, Manufacturing of porcelain insulator is tedious, porcelain insulators cannot be easily moulded in complex shapes resulting in limited flexible design [30]. Porcelain insulators are highly susceptible to vandalism especially gunshot attacks which can cause catastrophic mechanical failure and subsequent power outage [31]. Hydrophilic property of porcelain insulator allows the formation of pollution layer particularly in humid and coastal environments, which can significantly reduce their insulating capabilities leading to premature electrical breakdown [31].

III. POLYMER INSULATOR

Polymer insulators also known as composite insulators are gaining popularity in modern times offering a best alternative to traditional porcelain insulators. These insulators, which consist of fibre reinforced resin core and polymer housing have become very popular due to their superior performance characteristics and lower manufacturing cost [32].

A. Material Composition and Manufacturing

polymer insulators are composed of fibre reinforced plastic rod covered with housing material and metal end fittings, Fiber reinforced plastic rod typically made from glass fibre embedded in an epoxy resin provides primary mechanical strength and structural integrity for the insulator [33].The core is then covered by polymeric housing usually made of silicon rubber, EPDM or other polymeric compounds which provides necessary electrical insulation and protection against environmental factors [33].Weather sheds of polymer insulators are made from same material as the housing and they are designed to have maximum creepage distance and shed water effectively. The end fittings of polymer insulators are made up of metal, galvanized steel or aluminium, which are crimped onto the fiberglass rod to provide robust mechanical connection to the transmission line. This composite structure of polymer insulator makes it more light in weight yet mechanically robust and electrically insulating component suitable for high voltage applications. Polymer insulators are manufactured through a sophisticated process which involves pultrusion for the fibre glass rod, followed by injection moulding or extrusion for polymeric housing [34].

B. Electrical Characteristics

Polymeric insulators exhibit excellent electrical characteristics compared to traditional porcelain insulators due to their hydrophobicity and better resistance to pollution flashover, This performance stems from their inherent hydrophobic nature of polymeric material which prevents the formation of continuous water film, thereby mitigating leakage currents and minimizing the risk of flashover even in heavily polluted or humid environments [35].Polymer insulators had exceptional dielectric strength and tracking resistance contributing to their superior electrical insulation properties ensuring reliable operation under high voltage stresses. The inherent hydrophobic properties of the polymer insulator facilitate efficient water shedding, thereby preserving high surface resistivity which in turn mitigate the risk of pollution flashover, Moreover their capacity to regain hydrophobicity following exposure to moisture and contaminants, makes them more suitable for environments susceptible to surface pollution [36].Polymer insulators exhibit uniform electric field distribution because of their optimized design, which mitigates stress concentrations, maintaining electrical stability, and reduces partial discharge activity, Furthermore, Optimized insulator configurations enhances electric field grading and alleviate localized electrical stresses, As a result of this optimizations in polymer insulators there is substantial reduction in failures arising from electrical stresses such as corona discharge and tracking, thereby improving long-term reliability and operational efficacy [37].

C. Mechanical Properties

Polymer insulators possess superior mechanical properties, including a high strength-to-weight ratio and flexibility, which makes them more suitable over conventional ceramic insulators and underpin their extensive adoption in modern power transmission systems. The fiberglass-reinforced epoxy core provides exceptional tensile strength, which enables the insulators to endure substantial mechanical loads without fracture moreover, their flexibility and impact resistance enable these insulators to effectively absorb shocks and vibrations, rendering them less prone to damage from vandalism or severe events. This robustness against dynamic stresses augments operational lifespan of polymer insulators and reduces maintenance needs, especially in seismically active or high-wind regions [38].

D. Environmental Performance

The chemical composition of polymeric materials possess inherent hydrophobicity, resulting in superior anti-pollution performance and resilience against environmental degradation, especially in high-humidity or industrially polluted environments. Low-molecular-weight (LMW) silicone molecules migrate from the bulk to the surface, encapsulating pollutant particles and thereby augmenting the insulator's hydrophobicity and contamination resistance, This dynamic migration enables the insulator to recover its hydrophobic properties post-exposure to contaminants [39].Such a self-cleaning mechanism reduces the necessity for routine maintenance and cleaning, consequently optimizing operational costs and bolstering system reliability Moreover, the polymeric housing typically silicone rubber strengthens the electrical performance through exceptional arc resistance and reduced surface erosion under severe environmental stresses [40].

E. Limitations

Despite numerous advantages of polymeric insulators, their long-term field performance remains susceptible to degradation mechanisms, including ultraviolet radiation, corona discharge, and moisture ingress etc. which can degrade the insulating material as well its properties, these degradations impair the insulator's electrical integrity, potentially resulting in increased leakage currents and flashover [41].

IV. COMPARATIVE ANALYSIS OF ELECTRICAL PERFORMANCE

A. Tracking and Erosion Resistance

Polymer insulators, particularly those made up of silicone rubber and ethylene propylene diene monomer (EPDM), demonstrate superior resistance to tracking and erosion compared to its porcelain counterparts, owing primarily to their intrinsic material characteristics that prevents the formation of conductive pathways [10].

B. Dielectric Strength

Dielectric strength is fundamental property of insulators, characterizing their capacity to withstand electrical stress without experiencing breakdown. Polymeric materials typically demonstrate superior intrinsic dielectric strength relative to porcelain, thereby exhibiting greater resilience to electrical over stresses [11], [14].

C. Flashover Voltage

Polymer insulators typically demonstrate superior flashover voltage performance under contaminated and wet conditions, whereas porcelain insulators prove more vulnerable to pollution flashovers because of their hydrophilic surface properties [10], [36]. In contrast to the hydrophilic surfaces of porcelain, the hydrophobic characteristics of silicone rubber-based polymer insulators facilitate the effective shedding of water and contaminants, thereby upholding insulation integrity and preventing the development of conductive paths that led to flashover [8], [42]. This property confers particular advantages in highly polluted environments, where polymer insulators outperform conventional porcelain counterparts in alleviating pollution-induced flashovers [10].

D. Leakage Current

Polymeric insulators demonstrate very lower leakage currents compared to porcelain insulators, owing to their intrinsic hydrophobicity and capacity to recover these properties following exposure to contaminants moreover, this characteristic substantially mitigates the risk of dry-band formation and associated partial discharges, which are commonly responsible for flashover in porcelain insulators [39], [43].

V. COMPARATIVE ANALYSIS OF MECHANICAL AND PHYSICAL PROPERTIES

A. Weight And Dimensions

Polymer insulators exhibit substantially lower weight than their porcelain counterparts, thereby facilitating simplified transportation and installation processes, this subsequently reduces infrastructure expenditures and improve versatility for deployment in rugged terrains [9].

B. Flexure Strength

Polymer insulators typically demonstrate superior flexural strength compared to porcelain insulators, because of their inherent flexibility and robust reinforced internal structure, which allows bending under mechanical loads without fracturing [9].

C. Compressive Strength

Although polymer insulators surpass porcelain counterparts in tensile strength, the latter generally display superior compressive strength owing to their dense and rigid ceramic composition, which offers greater resistance to crushing or compressive forces [18].

D. Tensile Strength

Polymer insulators exhibit superior tensile strength compared to porcelain insulators, primarily due to their fiberglass-reinforced epoxy core, which enables them to endure substantial mechanical loads and enhances their resilience against dynamic stresses. This intrinsic robustness reduces their vulnerability to brittle fractures, a common failure mode in ceramic materials subjected to mechanical stresses [14], [44].

E. Vandalism and Damage Resistance

Polymer insulators exhibit superior resistance to vandalism because of their inherent flexibility and non-brittle composition compared to their porcelain counterpart, which are highly susceptible to catastrophic brittle failure under mechanical shock [45].

VI. COMPARATIVE ANALYSIS OF ENVIRONMENTAL PERFORMANCE

A. UV radiation Effect

Although polymeric insulators generally exhibit pollution performance compared to their ceramic counterparts, prolonged exposure to ultraviolet radiation can trigger material degradation, characterized by surface chalking, cracking, and hydrophobicity loss, which compromises their long-term electrical performance [9].

B. Pollution Performance

Polymeric insulator exhibits better pollution performance as compared to ceramic insulators due to its inherent hydrophobicity and self-cleaning properties that prevents the formation of continuous conductive layers on their surfaces [9]. This characteristic is particularly beneficial in environments with high levels of contamination, where traditional porcelain insulators often require frequent cleaning or specialized coatings to maintain performance [38].

C. Temperature Extreme

Porcelain insulators typically exhibit superior thermal stability across a wide temperature range however, the performance of polymer insulators may be compromised by extreme thermal cycling, highly impairing their mechanical and electrical properties [45].

D. Hydrophobicity And Recovery

Polymeric insulators are highly hydrophobic while ceramic insulators are hydrophilic in nature moreover polymeric insulators had the property of regaining hydrophobicity This crucial characteristic differentiates polymer insulators from porcelain counterparts, which lack this inherent restorative capacity [46].

VII. COST BENEFIT ANALYSIS AND ECONOMIC CONSIDERATIONS

A. Initial Installation Cost

While the initial purchase price of polymer insulators can sometimes be comparable to or even higher than that of porcelain insulators, their reduced weight and simplified installation procedures often lead to lower overall installation costs, including expenditures on transportation, labour, and specialized equipment [9].

B. Lifespan And Replacement Cost

However, the organic nature of polymer insulators means they are susceptible to aging and degradation from environmental factors such as UV radiation, potentially leading to a shorter operational lifespan compared to the more robust porcelain insulators [38].

C. Maintenance Cost

The intrinsic hydrophobic properties and self-cleaning capabilities of polymer insulators significantly diminish the necessity for frequent cleaning and maintenance interventions, which are often required for porcelain insulators, especially in polluted environments [47].

VIII. CONCLUSIONS

In this paper comprehensive comparison of polymer insulator and porcelain insulators has been done. Various technical and performance parameters of both types of insulators has been studies in detail. We could see that the some technical parameters are comparable whereas some parameters are different in both the cases. User can decide the type of insulator based on their requirement, suitability, application, and also site conditions.

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ANNEXURE

Parameter	**Porcelain Insulator**	**Polymer Insulator**	**Remarks / Comparative Insight**
Material Composition	Inorganic alumina–silica ceramic; glazed surface	Organic composite of fiberglass core and silicone rubber housing	Polymer structure allows flexibility and hydrophobic surface renewal
Density & Weight	High density, heavy; requires strong tower design	Low density, lightweight	Polymer offers easier installation and reduced mechanical loading
Hydrophobicity	Hydrophilic; water film forms easily	Intrinsically hydrophobic with self-recovery ability	Polymer resists continuous wet film formation, reducing leakage risk
Pollution Performance	Poor in coastal or industrial zones; requires frequent cleaning	Excellent under polluted conditions due to hydrophobicity	Polymer suited for high-pollution environments
Leakage Current Behavior	Increases rapidly with contamination	Lower and more stable under identical pollution	Polymer maintains higher surface resistance
Flashover Performance (Wet Conditions)	Decreases sharply with wetting	Higher withstand strength in humid/foggy environments	Polymer's partial wetting pattern prevents surface bridging
UV & Environmental Aging	Stable under UV; glazing may erode slowly	Sensitive to UV and ozone; hydrophobicity gradually decreases	Requires UV-resistant formulations or coatings
Mechanical Strength	High compressive and tensile strength; brittle under impact	Flexible and resilient; resistant to shock and vibration	Polymer less prone to catastrophic breakage
Thermal Endurance	Excellent, no melting or softening	Moderate; prolonged heat exposure causes softening	Porcelain preferred for high-temperature zones
Maintenance Requirement	Periodic cleaning needed in polluted areas	Minimal maintenance; visual inspection sufficient	Polymer reduces life-cycle maintenance costs
Service Life	25–40 years typical	15–25 years typical depending on UV exposure	Porcelain more durable; polymer offers lower total cost in polluted zones
Failure Mode	Brittle fracture or puncture; catastrophic	Gradual surface erosion and tracking	Polymer failure less abrupt and safer
Overall Suitability	Ideal for dry or moderate climates	Best suited for coastal, tropical, or industrial environments	Selection depends on climate and maintenance strategy

Mr. Chavan Vrushank Santoshbhai completed his B.E. in Electrical Engineering from Gujarat Technological University, India. He is currently pursuing M.E. in Electrical Power Engineering at The Maharaja Sayajirao University of Baroda, India. He is undertaking his postgraduate project under the expert guidance of the Electrical Research and Development Association (ERDA) Vadodara, India. His research area focuses on high-voltage polymer insulator performance, and his interests include finite element analysis of electrical equipment and power system studies. He can be contacted at email: vrushank.msu@gmail.com

	Dr. Anil S. Khopkar is PhD in electrical engineering, working as “Asst. Director & Head of Division – R&D and Expert Services at Electrical Research and Development Association (ERDA), Vadodara. He is responsible for various research activities and technology development in areas of Power Systems, Renewable Energy, Product Development and Advanced Materials in field of electrical engineering. He also headed, High voltage Impulse laboratory, Extra High Voltage Partial Discharge laboratory, Cable laboratory, Instrument Transformer Laboratory, Transformer Laboratory as well as calibration laboratory. He has established various test laboratory like, HV Impulse, HV PD lab, Transformer test laboratory etc. He is Member of BIS technical committee of India for High Voltage Testing techniques (ETD 19) and chairman of BIS technical committee of India for Surge Arrester (ETD 30). He is also a member of IEC Technical committee “TC 99/JWG 13 – Insulation co-ordination for HVDC System”. He has published 42 research papers in national and international conferences and journals. He can be contacted at email: anil.khopkar@erda.org
	Mr. Hiren M. Patel received BE Electrical Engineering from the Maharaja Sayajirao University of Baroda, Vadodara in the 2008 and M. Tech in Electrical Engineering with specialization in power systems from Veermata Jijabai Technological Institute in the year 2011. He worked as an assistant professor from 2011-2013 in Parul Institute of Engineering and Technology. He is presently working as an assistant professor since 2013, in the department of Electrical Engineering, Faculty of Technology and Engineering Engineering, The Maharaja Sayajirao University of Baroda Vadodara Gujarat, India. Also, he is pursuing his PhD in Electrical Engineering from the MSU of Baroda, Vadodara in the field of Electromagnetic Launchers. His expertise spans electrostatic and electromagnetic field computations, high voltage engineering, electrical machines, electromagnetic launchers and power systems. He has published papers in reputed conferences and journals. He can be contacted at email: hiren.m.patel-eed@msubaroda.ac.in